Integrating Flight Dynamics & Control Analysis and Simulation in Rotorcraft Conceptual Design

Ben Lawrence
San Jose State University
NASA Ames Research Center,
Moffett Field, CA

Tom Berger
Mark B. Tischler
VMC Technical Area
Aviation Development Directorate
U.S. Army AMRDEC
Moffett Field, CA

Colin R. Theodore
National Aeronautics and Space Administration
NASA Ames Research Center
Moffett Field, CA

Josh Elmore
Andrew Gallaher
Concept Design and Assessment Technical Area
Aviation Development Directorate
U.S. Army AMRDEC
Huntsville, AL / Moffett Field, CA

Eric L. Tobias
San Jose State University
Aviation Development Directorate
US Army AMRDEC
Moffett Field, CA

ABSTRACT

The development of a toolset, SIMPLI-FLYD ("SIMPLIfied FLight dynamics for conceptual Design") is described. SIMPLI-FLYD is a collection of tools that perform flight dynamics and control modeling and analysis of rotorcraft conceptual designs including a capability to evaluate the designs in an X-Plane-based real-time simulation. The establishment of this framework is now facilitating the exploration of this new capability, in terms of modeling fidelity and data requirements, and the investigation of which stability and control and handling qualities requirements are appropriate for conceptual design. Illustrative design variation studies for single main rotor and tiltrotor vehicle configurations show sensitivity of the stability and control characteristics and an approach to highlight potential weight savings by identifying over-design.

NOTATION

J	Cost function for frequency response error
p	Aircraft body axis roll rate
q	Aircraft body axis pitch rate
r	Aircraft body axis yaw rate
u	Aircraft body X-axis velocity
v	Aircraft body Y-axis velocity
w	Aircraft body Z-axis velocity
$X_u, X_w,$ $Z_w, M_{\delta_e}, N_{\theta_{0T}}$	Stability Derivatives (semi-normalized) i.e. $X_u = \frac{1}{M}\frac{\partial X}{\partial u}$ $L_P = \frac{1}{I_{xx}}\frac{\partial L}{\partial p}$
ΔI_{xx}	Change in roll moment of inertia
ΔI_{yy}	Change in pitch moment of inertia
ΔI_{zz}	Change in yaw moment of inertia
ΔW	Change in Weight (lbs)
β_{1c_1}	Multi-blade coordinate rotor longitudinal flap angle (subscript for rotor number)
β_{1s_1}	Multi-blade coordinate rotor lateral flap angle
δ_e	Elevator control deflection
θ_{1_c}	Rotor lateral cyclic angle
θ_{1_s}	Rotor longitudinal cyclic angle
θ_0	Rotor collective angle
θ_{TR}, θ_{0T}	Tail rotor collective angle
θ	Aircraft pitch angle
ψ	Aircraft yaw angle
ϕ	Aircraft roll angle

Presented at the AHS 72nd Annual Forum, West Palm Beach, Florida, USA, May 17-19, 2016.

INTRODUCTION

Thorough studies of flight dynamics and control have been historically neglected in conceptual design processes (Ref. 1), primarily because the view has been that there is insufficient knowledge of the aircraft properties to create and include reasonable and useful mathematical models. This lack of flight dynamics modeling at the earliest stages of design disregards a potentially significant contributor to size, weight, and performance estimates for some design activities. It also defers flight dynamics, rotor response lags, and control authority considerations to later in the design process, which have led to problems during flight test (Ref. 2). The flight dynamics and control of an air vehicle are fundamentally a function of its inherent control power and damping characteristics and are typically augmented by the feed-forward and feed-back loops programmed into a flight control system. Predicting these characteristics of a yet-to-be-built air vehicle is a challenge at the conceptual design phase where limited data is available.

The work presented in this paper draws on lessons learned from Ref. 3 where a preliminary framework was developed for conducting flight dynamics and control (FD&C) analyses in conceptual design. The key conclusions were that there was a technical feasibility in defining FD&C models using conceptual design data and that the inclusion of a stabilizing control system is important, not only to make the very likely unstable bare-airframe rotorcraft stable, making subsequent analyses more tractable and meaningful, but its inclusion in terms of gains and actuator performance requirements are themselves very useful indicators for design.

This paper describes the evolution of the preliminary framework of Ref. 3 to a more comprehensive toolset SIMPLI-FLYD ("SIMPLIfied FLight dynamics for conceptual Design") to enable flight dynamics and control assessments early in the design and assessment cycle. SIMPLI-FLYD is a joint NASA and Army development and uses a suite of tools including NDARC (Ref. 4), MATLAB/Simulink®, CONDUIT® (Ref. 5), and X-Plane® (www.xplane.com) to automatically model and analyze rotorcraft configurations, configure stability and control augmentation systems, and to integrate the combined flight dynamic and control models in an X-Plane-based simulation. This feature allows pilot-in-the-loop, real-time simulation of conceptual designs.

The output of these analyses, in terms of which are most important, their form, and how they are used to influence a conceptual design evolution continues to be a key research question. Through a description of the development of SIMPLI-FLYD and its subsequent application to illustrative designs, the paper investigates these issues, highlights the capabilities of the methodology implemented, and explores the lessons learned.

TECHNICAL APPROACH

Figure 1 shows the architecture of the SIMPLI-FLYD toolset. The schematic identifies the primary components within the SIMPLI-FLYD process as well as the key interfaces to external components and processes. The dashed blue box indicates the tools and activities encompassed in an overall conceptual design process when considering the FD&C aspects. Stage (1) is the primary conceptual design activity using NDARC, in a future context this process might well be represented by a variety of other analyses encompassed in a Multi-disciplinary Design and Optimization (MDAO) environment to iterate on a design. In the context of this paper, stage (1) is the input for the current version of SIMPLI-FLYD that encompasses stages (2) through (6).

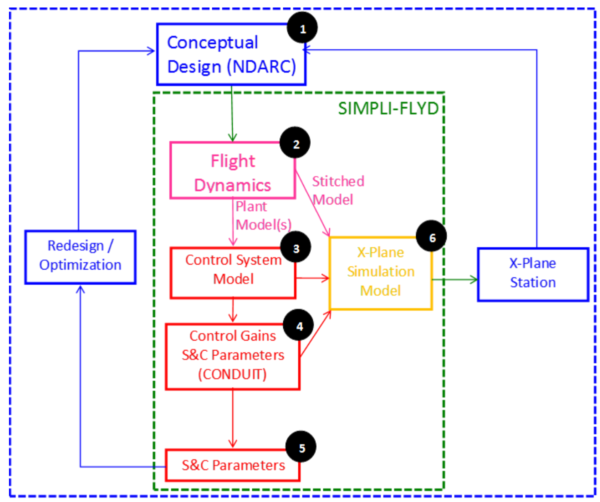

Figure 1 SIMPLI-FLYD Architecture for including stability and control analysis into conceptual design

The process generates two key outputs: set(s) of stability and control and handling qualities parameters, and an X-Plane compatible real-time simulation model vehicle for use in an X-Plane simulation station.

Flight Dynamics Modeling

A key requirement for the toolset was that it would ultimately be capable of modeling arbitrary rotorcraft configurations with various combinations of rotors, wings and other surfaces and auxiliary propulsion. Figure 3 shows a schematic of how the flight dynamic models are built up. The imported data consists of geometric, aerodynamic, and configuration data about the vehicle and pre-calculated data from a sweep of trim flight conditions from NDARC. Along with user input options, these data are processed to establish the number and type of components (rotors, wings etc.), and the number of model states and controls, amongst other parameters. The flight dynamic calculations then proceed to loop over the flight conditions and components calculating linear stability and control derivatives for each. For the rotors, this process uses a non-linear blade element model which is initialized at the NDARC calculated trim state from which the stability derivatives are calculated using numerical perturbation. For the other components: wings, aerodynamic surfaces and fuselage, a simplified direct calculation of the linear derivatives is used. The philosophy behind this approach was twofold: Firstly, the models are intended to be relatively simple for reasons of computational efficiency and also to be congruent with the level of modeling in NDARC. Secondly, the derivative calculation approach is intended to only add information that is not already available (i.e. flight dynamic characteristics) and repetition of calculations has been avoided as much as possible to minimize use of secondary parameters that may already exist in the main design database/model.

The total vehicle linear models are computed through the summation of the state-space 'A' and 'B' matrix terms from the various components. The linear models can be optionally 6-degree-of-freedom (6-DoF) rigid body states only or can include first order flapping equations, with one longitudinal and one lateral per "main" rotor, following the "hybrid" model formulation in Tischler (Ref. 5). As such, a single main rotor configuration would have 11 states, 9 rigid body states $(u, v, w, p, q, r, \varphi, \theta, \psi)$ and 2 rotor states $\left(\beta_{1c_1}, \beta_{1s_1}\right)$ as the tail rotor derivatives are always reduced to their 6-DoF contribution. Other configurations that feature two main rotors such as a tiltrotor or a tandem would contain 13-states, with 4 rotor states, and so on.

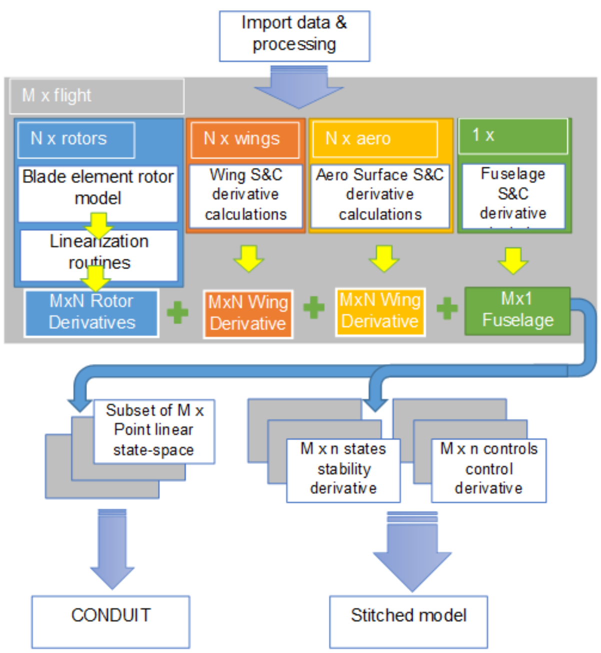

Figure 2 Schematic of the flight dynamics model build up process and output

For the control derivatives, an important simplification imposed for the analysis point models was that any vehicle had a fixed set of "controls" for the four primary roll, pitch, thrust and yaw response axes. The effects of multiple or redundant control effectors such as combinations of rotor controls and wing or aerodynamic surface controls are combined in advance of analysis at stages (3) and (4) using mixing matrices (the separate control derivatives are retained for use in the real-time model). This was important to make the control system requirements and optimization problem more tractable and to reduce the overall complexity for the initial implementation. The actuator characteristics are configurable for each analysis point model to allow for representation of different actuator classes (i.e. swashplate vs. aerodynamic surfaces) required for particular flight conditions/configurations. These are represented separately in the stitched model used for the X-Plane-based real-time simulations.

Model Verification

To verify that the flight dynamics models generated were representative, comparisons were made to higher fidelity legacy models. Figures 3 and 4 compare the hover roll, pitch, heave and yaw response of a UH-60A single main rotor configuration generated by SIMPLI-FLYD using input from an NDARC model to that extracted from the Army "FORECAST" code, as described in Ref. 7. To add a quantitative measure of the closeness of fit, a LOES (Lower Order Equivalent System) cost, J, is computed. This considers the cost of the fit of both the magnitude and phase of the frequency response over the 1-20 rad/s range, the critical frequency range of interest for handling qualities and flight control design. Ref. 5 states that J ≤ 50 "can be expected to produce a model that is nearly indistinguishable from the flight data in the frequency domain and the time domain", while costs of J ≤ 100 "generally reflects an acceptable level of accuracy for flight-dynamics modeling". The costs for the four UH-60A primary axis responses are all acceptable (≤ 100). Some differences become apparent at lower frequencies, however these are considered less significant as per the increasing MUAD (Minimum Unnoticeable Added Dynamics, Ref. 8) boundaries represented by the dashed lines. The boundaries are derived from piloted experiments and reflect that large differences in low frequency modes with long time periods are indiscernible by pilots.

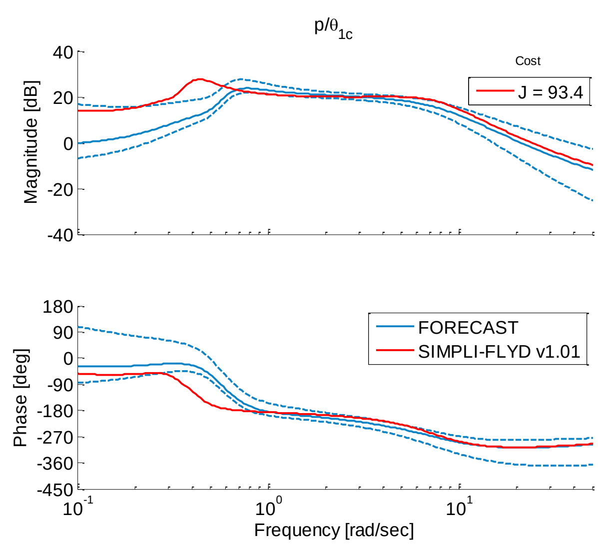

Figure 3 Roll rate frequency response comparison of UH-60A hover linear models extracted from SIMPLI-FLYD and FORECAST (MUAD boundaries dashed)

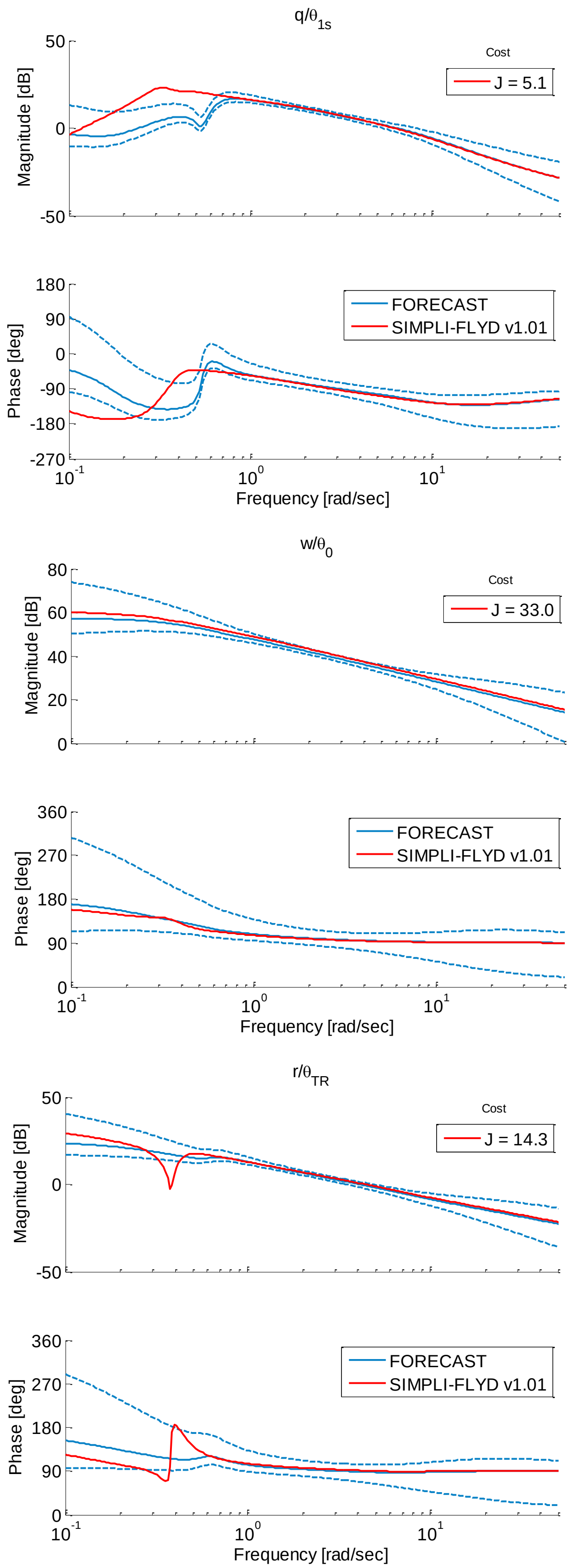

Figure 4 Pitch rate, vertical velocity and yaw rate frequency response comparison of UH-60A hover linear models extracted from SIMPLI-FLYD and FORECAST. (MUAD boundaries dashed)

Figures 5 and 6 show frequency response comparisons for a 32,000lb class Tiltrotor model compared to a linear model of the same vehicle extracted from the high fidelity HeliUM multi-body dynamics code described in Ref. 9. The flight condition is for the tiltrotor in airplane mode (nacelle tilt = 0 degrees), at a speed of 160kts. In this configuration, the aircraft is flying wing-borne and the control effectors are the aileron, elevator and rudder aerodynamic control surfaces. The comparisons are generally good for the tiltrotor both qualitatively and quantitatively. The LOES cost is somewhat high for the lateral velocity response to rudder where the main difference is in the magnitude. This brief snapshot of model comparisons are reflective of a wider set that have been made as part of this work which have also shown similar levels of comparison and provides confidence that the tool is able to capture the primary flight dynamic features of a range of rotorcraft types, sizes and flight conditions.

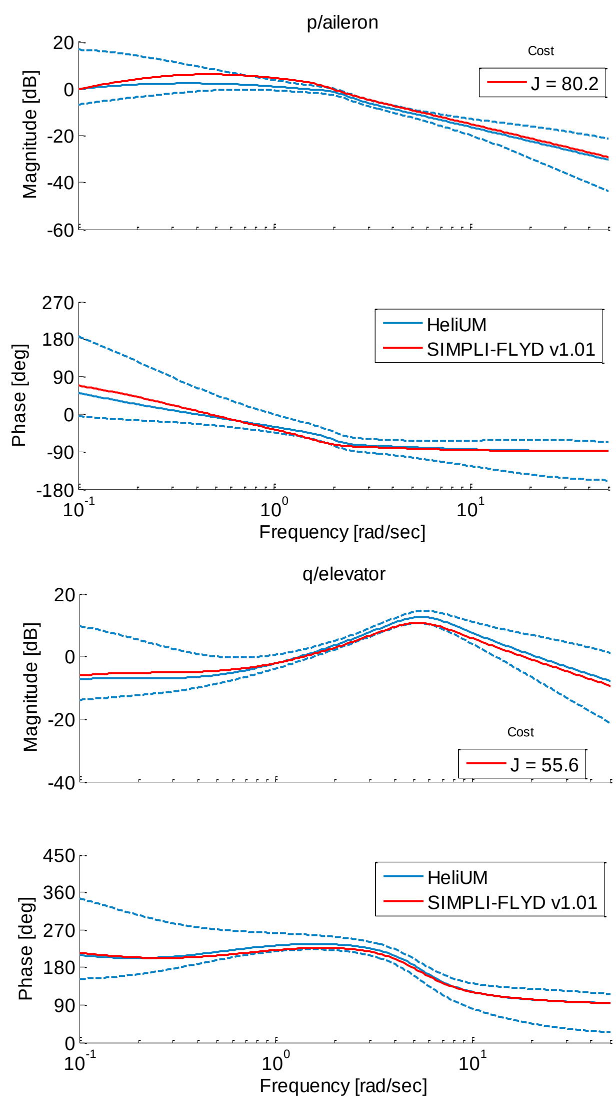

Figure 5 Roll and pitch rate frequency response comparison of 32,000lb tiltrotor at 160kts linear models extracted from SIMPLI-FLYD and HeliUM. (MUAD boundaries dashed)

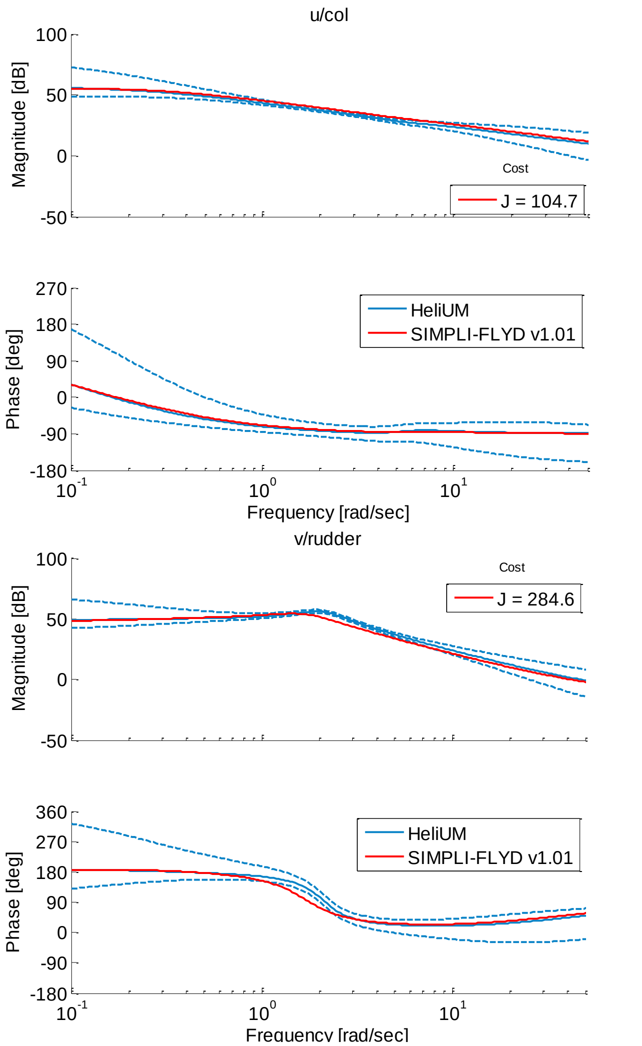

Figure 6 Longitudinal and lateral velocity frequency response comparison of 32K tiltrotor at 160kts linear models extracted from SIMPLI-FLYD and HeliUM. (MUAD boundaries dashed)

CONTROL SYSTEM ARCHITECTURE, OPTIMIZATION AND S&C ANALYSIS

The control system applied to the vehicle model at stage 3 in Figure 1 is based on an explicit model following architecture shown in Figure 7, which consists of independent feed-forward and feedback paths.

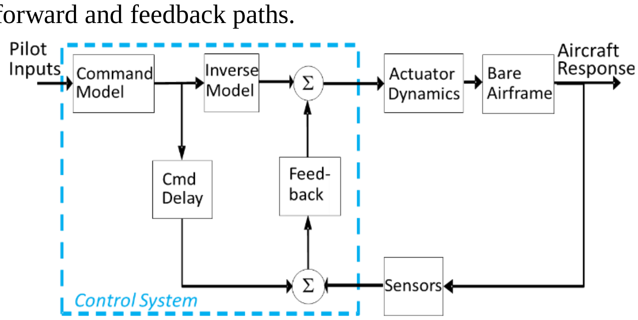

Figure 7 Explicit Model Following Architecture

The feed-forward path includes the command model which sets the response type of the aircraft.

Table 1 shows the response types used in each axis and flight regime.

Table 1. Control system response types for various axis and flight modes

	Rotor-Borne		Wing-Borne
	Hover	Forward-Flight	Forward-Flight
Roll	RCAH[a]	RCAH	RCAH
Pitch	RCAH	RCAH	Angle-of-Attack-Command
Yaw	RCDH[b]	Sideslip-Command	Sideslip-Command
Thrust	RCHH[c]	Open-loop	Open-loop

[a]RCAH = Rate-Command/Attitude-Hold
[b]RCDH = Rate-Command/Direction-Hold
[c]RCHH = Rate-Command/Height-Hold

The command model in each axis sets the desired dynamics of the closed-loop system. This is achieved using lower-order command-model responses. The order of the command model (either first-order or second-order) is chosen based on the inherent order of the aircraft response. For example, for a rate command response type in the roll axis, a first-order command model is used:

$$\frac{p}{\delta_{\text{stk}}} = \frac{K_{\text{lat}}}{\tau_{\text{lat}} s + 1}$$

Whereas for example, sideslip command is used in the yaw axis at forward flight, and a second-order command model is used:

$$\frac{\beta}{\delta_{\text{ped}}} = \frac{K_{\text{ped}}}{s^2 + 2\zeta_{\text{ped}}\omega_{\text{ped}} s + \omega_{\text{ped}}^2}$$

The parameters of the command model are the gain K, time constant (first-order only) τ, natural frequency (second-order only) ω, and damping (second-order only) ζ. These parameters are tuned to meet the piloted response criteria, such as piloted bandwidth, damping, quickness, and stick sensitivity requirements of ADS-33E or MIL-STD-1797B (Refs. 10 and 11). A good model following cost ensures that the actual closed-loop response of the aircraft tracks the commanded response.

The feed-forward path also includes a lower-order inverse of the on-axis bare-airframe response used to generate the actuator commands needed to follow the command model. The inverse plant dynamics are based on an accurate lower-order equivalent system (LOES) representation of the bare-airframe response in the frequency range around crossover (typically around 1-10 rad/sec). The order of the inverse model (either first-order or second-order) is chosen based on the inherent order of the aircraft response, with first-order being used for roll rate, pitch rate, yaw rate, and vertical velocity, and second-order being used for sideslip and angle-of-attack.

The feedback path of the control laws is optimized independently to meet the stability, damping, gust rejection, and performance robustness requirements. The feedback path in each axis is comprised of proportional, integral, and derivative (PID) gains.

Additional elements of the block diagram include the actuator and sensor blocks. Four primary actuators are including in the block diagram for the four primary control axes (roll, pitch, yaw, and collective/thrust). Actuators are modeled as second-order systems with position and rate limits:

$$\frac{\delta_{\text{act}}}{\delta_{\text{cmd}}} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Sensor models are included on each signal fed back to the control system. Sensors are modeled as second-order systems with default values of natural frequency and damping of ω_n = 31 rad/sec and ζ = 0.7, as well as a sampling time delay of 0.02 sec.

Setup and optimization of the control laws is fully automated within CONDUIT®. First, the bare-airframe model is decoupled to maintain separate results for each axis. It is a safe assumption that a well-designed input mixer and control system will decouple the aircraft responses. Next, the control system is optimized for each axis, starting with the feedback path to stabilize the system, and then with the feed-forward path to meet the handling qualities requirements. In each axis, key metrics are used to assess the level of over- or under-design in the control system. In the case of feedback, the metrics used are the control system's ability to reject disturbances (disturbance rejection bandwidth) and the control system's performance robustness (crossover frequency). These are the two metrics that provide a measure of the key benefit of the feedback path of the control system. Starting with a baseline required value for each of those two specification (defining 0% over-design), the requirements are progressively increased (more over-design) until a feasible design can no longer be achieved. If the baseline design cannot be met, the requirements are decreased (under-design) until a feasible solution is achieved. After the feedback path is optimized, the feed-forward path is optimized using the same approach. In the case of the feed-forward path, the specifications used to assess over-design are piloted bandwidth, quickness, and control power. These three metrics are the key requirements that cover the speed of response to piloted input, and provide a measure of the benefits of the feed-forward path of the control system.

The handling qualities specifications used to drive the control system optimization are divided by aircraft type, flight regime, control axis, and feedback or feed-forward. Table 7 through Table 12 in the Appendix list all of the specifications used. Specifications boundaries were chosen from ADS-33E for Moderate Agility / All Other MTEs. Specifications from MIL-STD-1797B were chosen for Category B flight (nonterminal flight phases that are normally accomplished using gradual maneuvers) and Air Vehicle Classes I (small, light), II (medium weight, low-to-medium maneuverability), or III (large, heavy, low-to-medium maneuverability).

Once the control system optimization is complete, the block diagram parameters (feedback gains, feed-forward gains, inverse model parameters, etc.) are saved. Also the HQ specification results of the control system optimization, given individually for each axis, including the amount of over- or under-design are saved. First, the "Phase" (Ref. 5) at which the optimization finished is recorded, which gives an indication of whether or not all of the specifications were met. The optimization process is broken into three phases. During Phase 1, CONDUIT tunes the gains to meet all of the Hard Constraints (stability specifications). If the optimization ends while still in Phase 1, then one or more of the stability specifications could not be met. The specifications that limit the optimization from continuing to achieve a higher level of over-design is identified at this stage.

If all the Hard Constraints are met, CONDUIT will move to a second phase. During Phase 2, CONDUIT will tune the gains to meet all of the Soft Constraints (handling qualities specifications). Again, if the optimization ends while in Phase 2 this means one or more of the handling qualities specifications could not be met and the specification that is limiting the optimization is identified for review.

Finally, after all of the specifications are met CONDUIT moves to Phase 3, and tunes the gains to reduce the Summed Objective ("cost of feedback" or performance specifications), thus ensuring the design meets the requirements with the minimum amount of overdesign. If the optimization ends in Phase 3, then CONDUIT was able to tune the gains to meet all of the specifications.

EXAMPLE RESULTS USING SIMPLI-FLYD

This section will present two example case studies using NDARC models of a UH-60A and a 32,000lb tiltrotor to demonstrate the SIMPLI-FLYD toolset.

UH-60A Tail Rotor Size Variation Study

The first example is for a ±20% and ±50% variation in the tail rotor blade area (proportional radius and chord, tip velocity maintained via rpm adjustment) for the NDARC UH-60A model as depicted in the schematics in Figure 8. Also note the fuselage length and empennage location were adjusted accordingly to maintain separation between rotors and surfaces and to ensure surfaces remain in their correct attachment point.

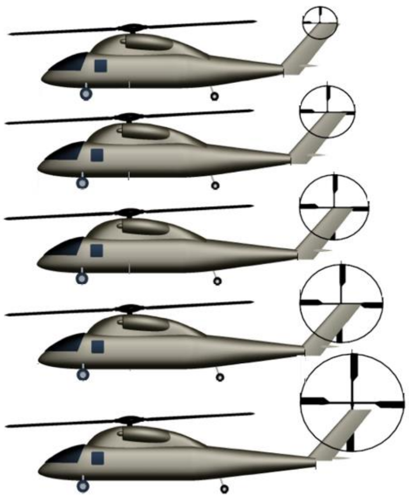

Figure 8 Illustration of NDARC UH-60A tail rotor radius/chord variation for SIMPLI-FLYD analysis

The impact of the variations in the configuration on the resulting aircraft weight, c.g. and moments of inertia were also predicted. These effects were captured jointly by a combination of NDARCs built-in weight equations and a separate weight and balance analysis of the configurations after their layout had been finalized as per Figure 8. The resulting weight and inertia changes are presented in Table 2. The resulting weight changes for this case are fairly minimal (less than 50lbs) but variations of up to nearly ±10% are observed for the yaw and pitch inertias.

Table 2 Effect of tail rotor size variation on UH-60A moments of inertia and weight

Tail rotor size:	-50%	-20%	+20%	+50%
ΔI_{xx} (%)	-0.074	-0.009	-0.007	-0.143
ΔI_{yy} (%)	-9.78	-4.17	+4.63	+11.46
ΔI_{zz} (%)	-9.64	-4.11	+4.59	+11.3
ΔW (%)	-0.226	-0.081	+0.106	+0.246

The variations in geometry, mass and inertia were applied to the NDARC models and the output passed to the SIMPLI-FLYD toolset. The response in the trim behavior is shown in Figure 9. This is an important first check as ability to trim within reasonable limits is an important design criterion. In this case, it can be seen that the 50% reduced tail rotor has a particularly large collective setting to achieve trim (the missing points for this case above 100kts are because no trim solution was achieved). Here, the NDARC rotor model thrust does not limit due to stall (stall effects power in NDARC but is considered in the HQ analysis) and thus inputs can be continually increased until a trim solution is reached. Closer inspection of the NDARC output for this case had shown that this rotor had exceeded thrust limits. The other variation cases were less extreme in the trim requirements although the 20% reduced case has a relatively large 5-6 degree increase in collective at hover. Despite these issues, all the variation cases are retained for the purposes of this example study.

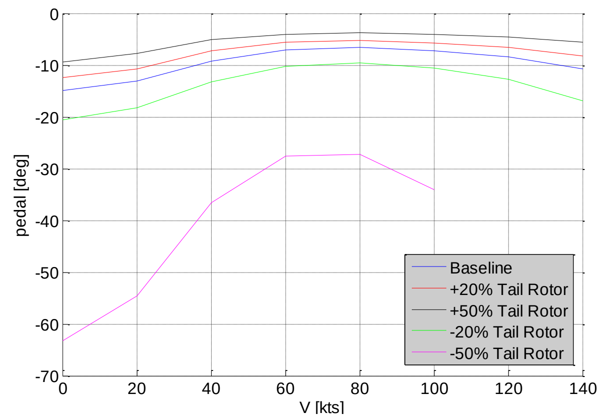

Figure 9 Tail rotor collective pitch required for trim for NDARC UH-60A with variations in tail rotor size

Figure 10 shows the effect of the tail rotor size variation on the bare-airframe flight dynamic and control characteristics. As the focus for this example are the primary yaw axis characteristics in the hover, the two key influential stability and control derivatives, N_r and $N_{\theta_{0T}}$ (yaw rate damping and yaw moment due tail rotor collective) are presented (the forward flight derivatives are retained for comparison). The trends in the derivatives are as expected, with control power and damping varying almost proportionately with the change in tail rotor size (the moment arm is also changing).

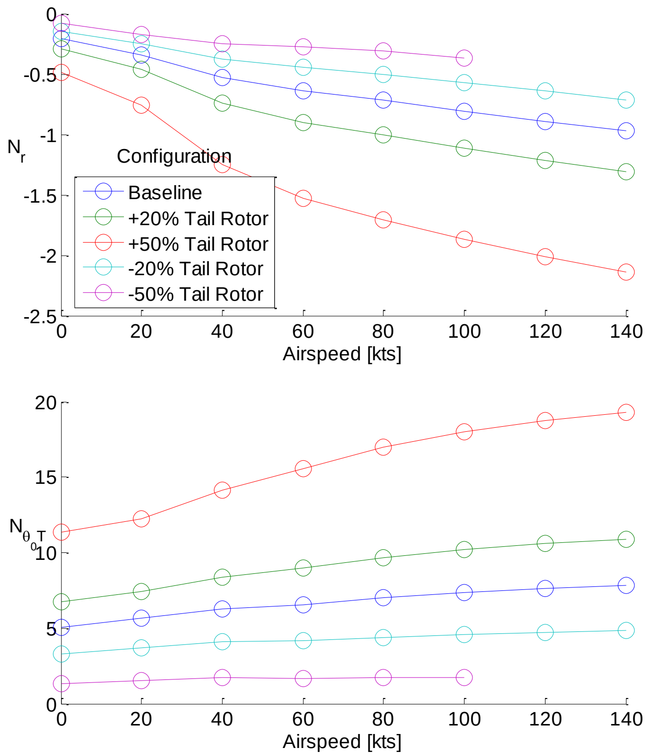

Figure 10 SIMPLI-FLYD yaw axis stability & control derivatives for NDARC UH-60A tail rotor size changes

The results of the CONDUIT optimization and analysis of the models at the hover flight condition with tail rotor size variations are shown in Figure 11 for feedback and Figure 12 for feed-forward. The results show that for a similar level of actuator usage (as seen on the "OLOP" PIO criteria and Actuator RMS specification), as tail rotor size increases, higher disturbance rejection bandwidth and crossover frequency values are achievable. This comes at the cost of lower stability margins for the larger tail rotor configurations, but still within Level 1. This is also shown in Table 3 by the increased level of feedback over-design for increased tail rotor size. In fact, the 50% reduced tail rotor case cannot even meet the minimum requirement and therefore has 30% under-design.

Sensitivity is also observed for piloted bandwidth, Quickness, and control power specifications in the feed-forward specifications in Figure 12. Here it can be seen that all the configurations are not able to achieve Level 1 bandwidth as per the ADS-33E-PRF hover/low speed utility class rotorcraft specifications in Ref. 10. All the tail rotor size cases are unable to achieve better than Level 2 yaw quickness whereas all the cases are able to achieve Level 1 control power in yaw (the -50% tail rotor is borderline Level 1/2). This result is consistent with the application of the larger tail rotor, where the greater thrust of the larger tail rotor is able to impart greater yawing moments, augmenting the medium amplitude response quickness characteristics and large amplitude control power. The trends for bandwidth with the tail rotor size variation are similar, with the bandwidth reducing/increasing accordingly with size.

It is worth noting that even the +50% tail rotor case cannot achieve Level 1 yaw bandwidth and attitude quickness. This observation aligns with a widely held opinion in the HQ community that the current yaw axis bandwidth and attitude quickness requirements are too demanding. As such, Ref. 12 shows data that support this position along with proposed relaxations of the yaw axis bandwidth and attitude quickness boundaries for an upcoming update to the HQ requirements in ADS-33F. The tool yaw bandwidth and quickness boundaries will be updated accordingly when ADS-33F is published.

The other key output of the CONDUIT analysis is manifested in the HQ requirements “design margins” (DM), these are equivalent to the percent over/under design and are computed for each control axis analyzed and for both the feedback and feed-forward control paths. Table 3 shows the yaw axis design margins for the NDARC UH-60A tail rotor size variations for the hover flight condition. For the FB specifications the baseline and larger tail rotors have significant design margin which reduces as the tail rotor size is reduced.

Table 3 CONDUIT Yaw axis Design Margins (DMs) for NDARC UH-60A tail rotor size variation at hover

Tail Rotor size:	-50%	-20%	BL	+20%	+50%
Feed-forward	-90%	-70%	-60%	-40%	-20%
Feedback	-30%	+20%	+50%	+70%	+100%

For the baseline and even the increased tail rotor size configurations, it can be seen there is a significant under design for the feed-forward path. The limiting specification being the Level 2 yaw bandwidth and quickness requirements. Decreasing tail rotor size leads to a further reduction in the under-design (negative) design margin. There is +50% margin in the feedback design margin for the baseline which, as already highlighted, becomes an (-)30% under design margin for the smallest tail rotor and doubles to an 100% over design for the largest tail rotor.

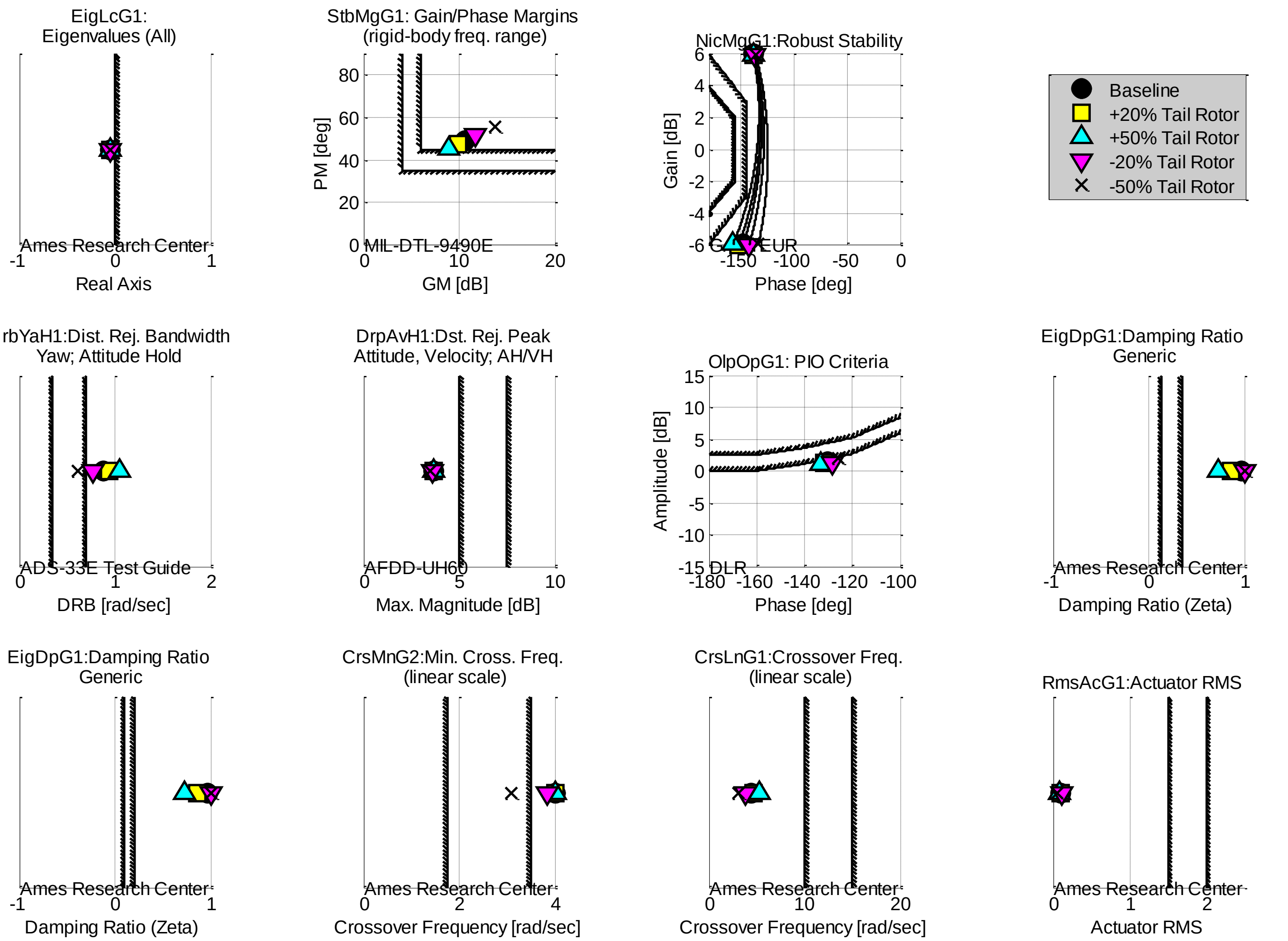

Figure 11 CONDUIT yaw axis feedback (FB) HQ window for NDARC UH-60A tail rotor size variation at hover

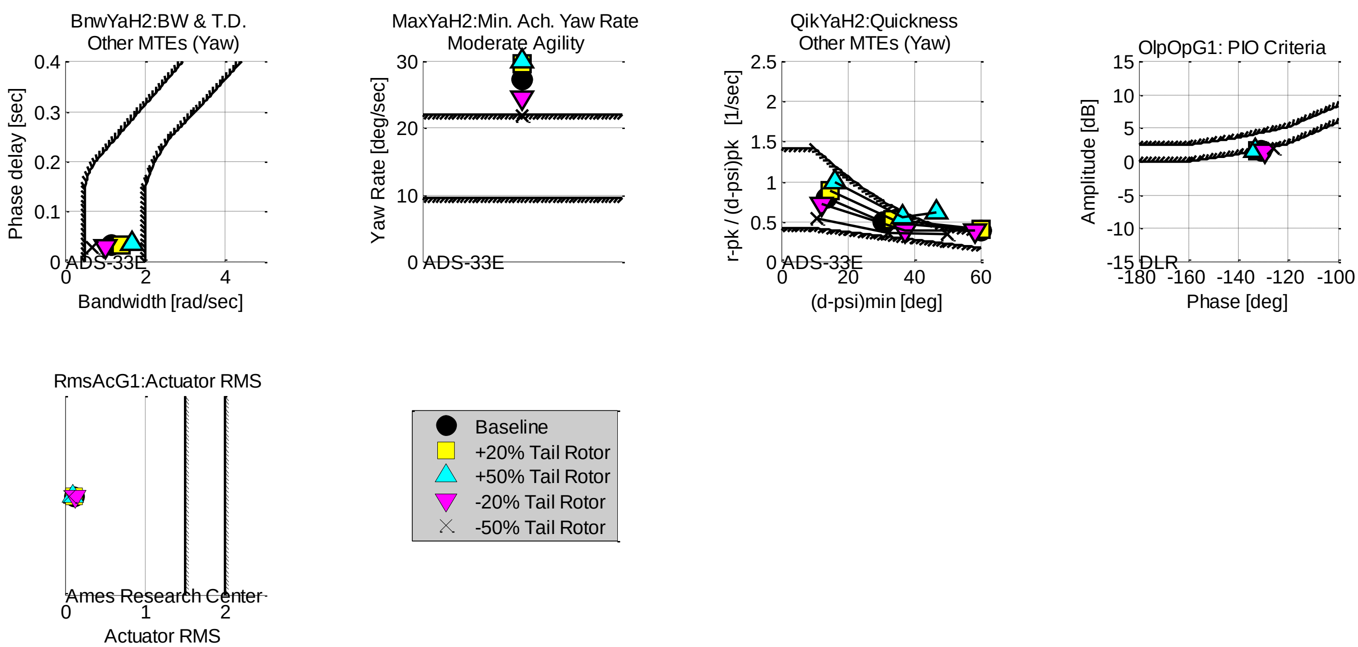

Figure 12 CONDUIT yaw axis feed-forward (FF) HQ window for NDARC UH-60A tail rotor size variation at hover

Tiltrotor Tail Surface Size Variation Study

A second example of SIMPLI-FLYD usage is via a variation in the tail area (proportional span and chord) for a NDARC 32,000lb (32K) tiltrotor model as depicted in Figure 13. This variation was somewhat simpler than the UH-60A example as the tail was simply scaled with no other adjustments to the airframe. The variations examined were a +20% increase and -20% and -50% area reductions. Although this example study case was primarily aimed at a pitch axis evaluation, the tail size variation also affected the lateral-directional flight dynamics and control (not shown) due to the “V-tail” configuration. The results shown are for elevator actuators (30% flap chord ratio) where the baseline position saturation and rate limits were ±20deg and ±20 deg/s.

Figure 13 Illustration of NDARC 32K tiltrotor tail size variation for SIMPLI-FLYD analysis

Table 4 Effect of tail rotor size variation on 32K tiltrotor moments of inertia and weight

Pitch	-50%	-20%	Baseline	+20%
ΔI_{xx} (%)	-1.23%	-0.61%	-	+0.74%
ΔI_{yy} (%)	-27.95%	-11.73%	-	+12.30%
ΔI_{zz} (%)	-10.81%	-4.56%	-	+4.83%
ΔW (%)	-1.67%	-0.70%	-	+0.73%

The effect of the tail size variation, as summarized in Table 4, had a more significant impact on the vehicle mass and inertia characteristics than were seen for the tail rotor changes on the UH-60 example. The changes in weight were of the order of hundreds of pounds as opposed to tens (albeit for a vehicle twice the weight), this led to weight deltas in the order of 1-2%. The yaw and pitch inertia differences were also larger, with deltas in the range of 10-20% of the baseline design. As for the UH-60A example, it is first informative to consider the trim plot in Figure 14, in this case elevator angle for an airplane mode speed range. The results are as expected, with the smaller tail requiring greater elevator angle for trim and vice versa. At the 160kts flight condition, the differences in trim between the configurations are not particularly large (2-3 degrees) but grow as the stall speed is approached.

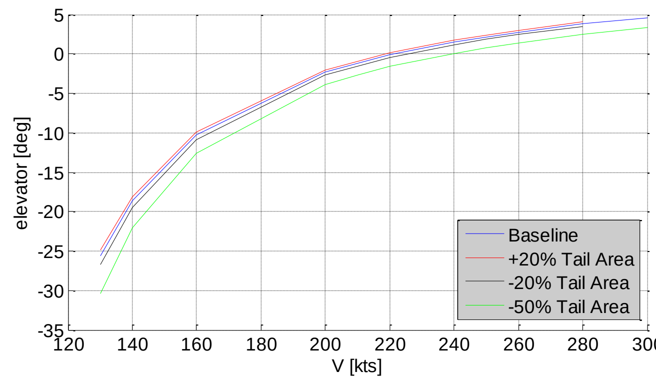

Figure 14 Elevator angle required for trim for NDARC 32K tiltrotor with variations in tail rotor size

The impact on the bare-airframe flight dynamic and control characteristics is illustrated in Figure 15. Here the key primary longitudinal stability and control derivatives are shown for the airplane mode speed range of 140-300kts. Again there is almost a directly proportional relationship of the tail size with many of these derivatives governing the vehicle pitch and vertical axis damping, stability, and control power.

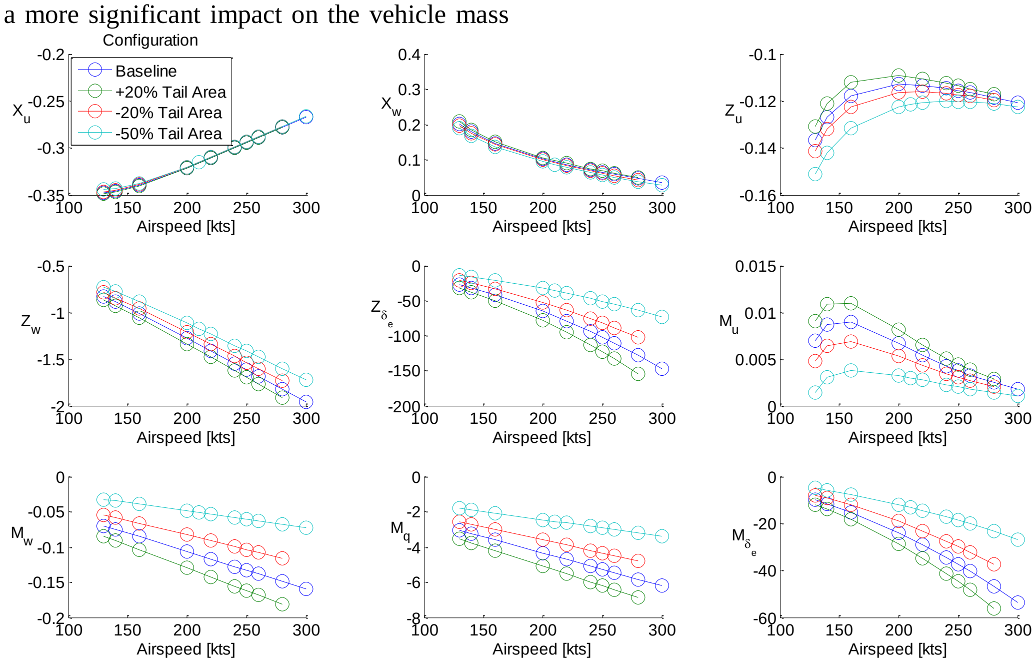

Figure 15 SIMPLI-FLYD Longitudinal stability & control derivatives for NDARC 32K tiltrotor tail size changes

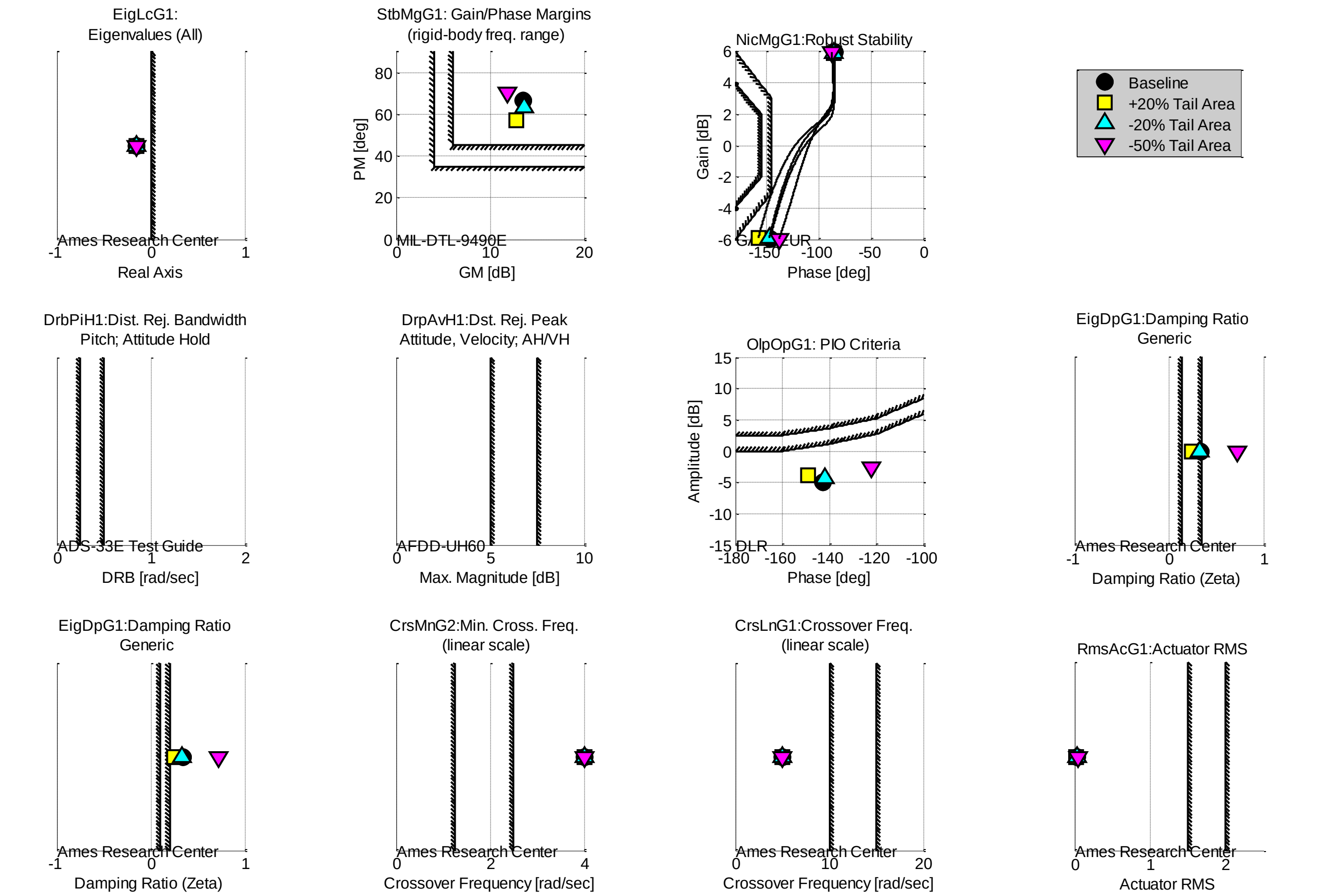

Figure 16 CONDUIT pitch axis feedback (FB) HQ window for NDARC 32K tiltrotor tail size variation at 160kts

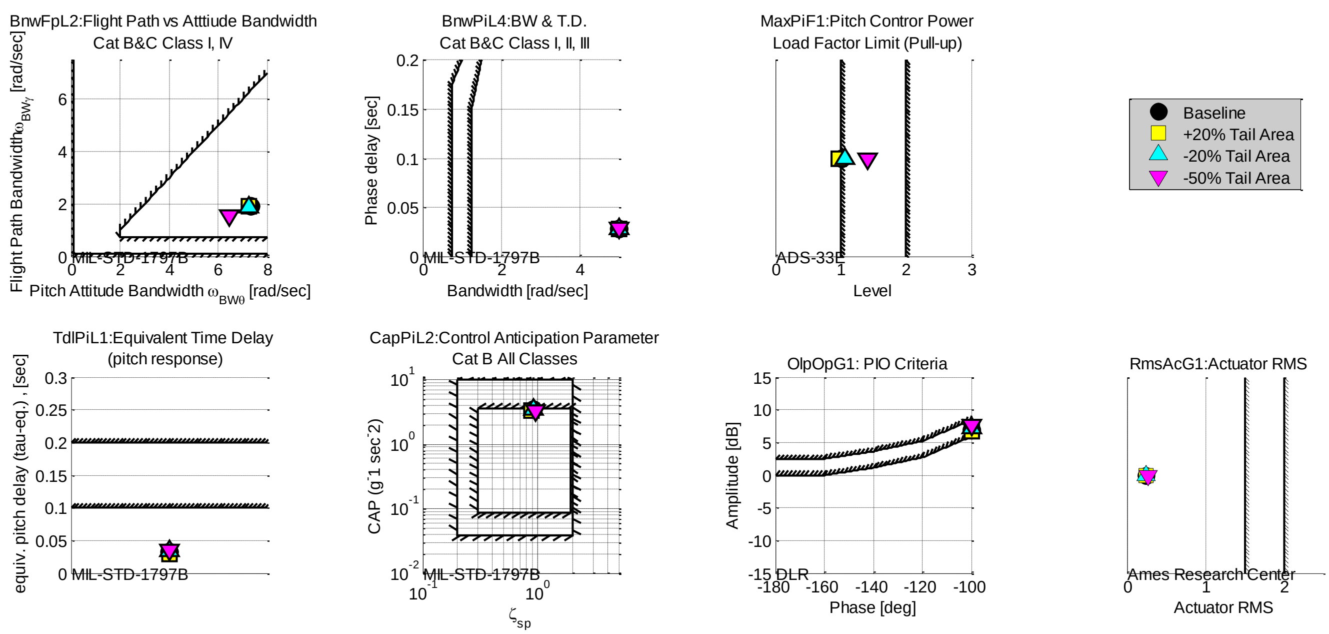

Figure 17 CONDUIT pitch axis feed-forward HQ window for NDARC 32K tiltrotor tail size variation at 160kts

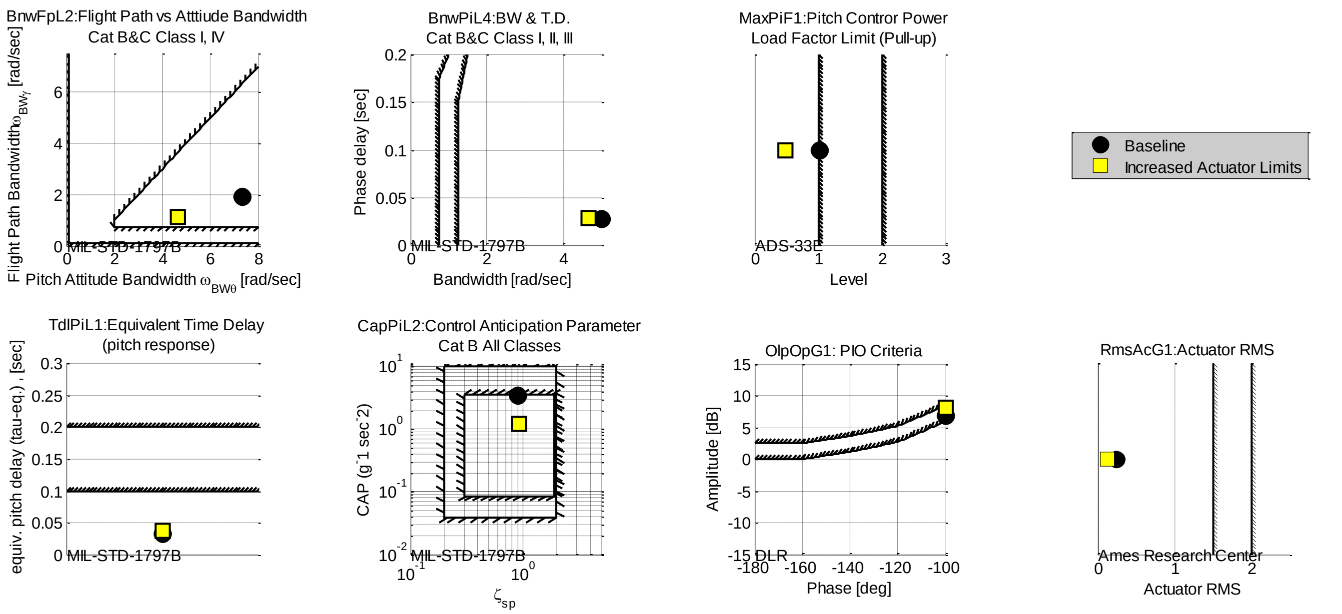

Figure 18 CONDUIT pitch axis feed-forward HQ window for NDARC 32K tiltrotor actuator variation at 160kts

For the CONDUIT analysis outputs in Figure 16 and Figure 17, large changes do not occur for the pitch axis forward flight feedback specification results in response to the tail size variation. Sensitivities are observed for the feed-forward requirements. For the load factor limit/pull-up requirement, the 20% increased tail case is on the Level 1/2 boundary with the result moving steadily more Level 2 for the baseline, 20% and 50% reduced tail cases.

Overall, it is notable that apart from the 50% reduced tail, most of the configurations remain mostly or close to Level 1. In this case, it is more useful to evaluate the design margins as these are more likely to highlight the differences between the configurations. These are shown in Table 5 and show that at 160kts, the baseline aircraft has plenty of design margin for the feedback specifications (a maximum limit of +200% was applied) but has a slight under design margin (10%) for the feed-forward specifications. Varying the tail size leaves the feedback design margins unaltered but it does affect the feed-forward specifications, increasing the tail size mirrors the result observed for the load factor limit/pull-up requirement plot described earlier, in that all the specifications are Level 1 with minimal margin. Decreasing the tail size reduces the feed-forward DM.

It is important to highlight the influence of the actuator characteristics as an important factor in these results. When using the linear models, the amount of control deflection is the critical factor in limiting the overall control response; and because of the model-following control laws which effectively “negate” the bare airframe dynamics via the inverse models it uses, many of the response requirements end up being a function of the vehicles’ control authority to track the desired response being specified by the command model.

Table 5 CONDUIT pitch axis Design Margins (DMs) for NDARC tiltrotor tail size variation at 160kts

	-50%	-20%	Baseline	+20%
Feed-forward	-50%	-10%	-10%	0%
Feedback	+200%	+200%	+200%	+200%

An example of this sensitivity to actuators is illustrated in Figure 18 which compares the tiltrotor at 160kts with the baseline elevator actuators and ones with increased saturation and rate limits of ±30deg and ±30 deg/s. Only the feed-forward specification results are shown, but a strong sensitivity (much larger than seen for the tail geometry changes in Figure 17) in the load factor limit/pull-up control power requirement is observed. This requirement is pushed well into the level 1 region from borderline level 1/2 by increasing the allowable elevator control deflection/rate limits. Again, it is important to compare the design margins for the two cases, shown in Table 6. As for the tail size variation, there is no variation in the feedback design margin, however, a significant boost in the design margin is observed, with the added control authority of the increased actuator position and rate limits now conferring a +50% design margin.

Table 6 CONDUIT pitch axis Design Margins (DMs) for NDARC 32K tiltrotor actuator variation at 160kts

	Baseline	Increased
Feed-forward	-10%	+50%
Feedback	+200%	+200%

X-PLANE REAL-TIME SIMULATION

A further feature of the SIMPLI-FLYD toolset is the capability to integrate a number of the elements to facilitate a piloted real-time simulation of the vehicle. The X-Plane real-time simulation consists of a MATLAB/Simulink based "stitched model" flight dynamics model combined with control system that features a gain scheduled versions of the control laws optimized at the CONDUIT analysis stage. A stitched model (Refs. 13 and 14 are examples used and developed by the authors previously) is a method by which multiple linear state-space models are "stitched" together via their constituent trim states and stability and control derivatives being lookup table functions of flight condition and configuration. This forms what is known as a quasi-linear parameter varying model (qLPV) (Ref. 15). This type of models offer the ability to represent changing trim and dynamic characteristics across the flight envelope in a model architecture that has a more direct correlation with the simplified analysis point models. The approach also has added advantages in that it avoids some of the overheads in complexity, robustness and computational demand that more sophisticated non-linear real-time models require – an important consideration in the context of rapidly evaluating lower complexity models of wide variety of configurations in a conceptual design methodology.

The stitched model is integrated along with additional modeling for undercarriage, powerplant and actuators into a real-time version of the control laws that feature scheduling of the command model and feedback gains with flight condition and configuration. The anchor points for the gain scheduling are specified by the user and are the result of CONDUIT optimizations at point models through the desired envelope. The real-time control system also has a number of features to enable gross maneuvering (loops, rolls etc), protection against integrator wind up as well as mode switching, blending and logic for transition between weight-on-wheels, hover/low-speed and forward flight modes. The simulation runs in real-time from the MATLAB/Simulink GUI console and communicates data to/from the X-Plane simulation environment using a shared memory interface developed with the support of Continuum Dynamics Inc. and a number of NASA Ames Research Center Aeromechanics office interns. X-Plane provides the interface to the pilot inceptor hardware and provides the graphical scene as depicted in Figure 19, or can be run on a desktop computer with off-the-shelf gaming pilot control sticks.

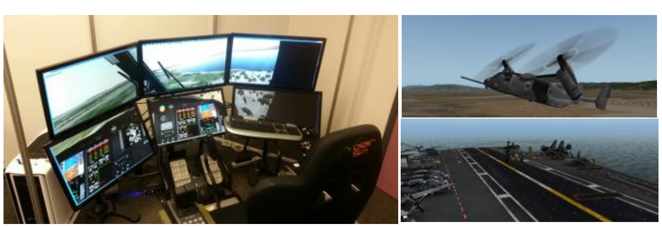

Figure 19 Typical X-Plane fixed-based simulator station

The X-Plane simulation capability is intended to augment the overall conceptual design process by offering an opportunity to get a "sense" of how different flight dynamics and control characteristics of the conceptual designs manifest themselves when flown pilot-in-the-loop. The piloted simulation is not intended for rigorous handling qualities analyses but it provides an environment where the flight dynamic characteristics can play a part in examining design tradeoffs when flown in representative operational scenarios.

DISCUSSION

The example results have demonstrated a number of potential use scenarios of the SIMPLI-FLYD toolset and allows the conceptual designer to see the impact of design choices on S&C and HQ aspects of rotorcraft conceptual designs. The UH-60 example showed how potential HQ issues might be identified and also provide mechanisms and metrics to effect and evaluate design changes. It is noted that the weight results for the UH-60A tail rotor variation showed a relatively weak sensitivity. The weight equations used in NDARC for this analysis are a weak function of the tail rotor radius directly, the more dominant parameters being the main rotor radius, main rotor tip speed, and main drivetrain torque limit. The changes to the tail rotor in this scenario are at more component-level for HQ concerns, and the weight dependencies are not fully configured for such a study. In other words, the sizing of the tail rotor itself is assumed to be mostly a function of the main rotor and drivetrain in the weight model. The tiltrotor example showed an "inverse" scenario where desired HQs were established but any potential overdesign margins in the HQ and control aspects can be evaluated in the context of seeking reduced design weight.

The example cases shown represent only a small sub-set of the overall design problem that would feature multiple inputs and outputs, simultaneously incorporating multiple axes, flight conditions and potentially multiple flight configurations. With the establishment of the SIMPLI-FLYD framework, future research can now squarely focus on addressing the questions regarding the issue: How are the HQ factors used to feed back to the conceptual design process? The challenge begins with selection of the HQ specifications. The current version of the SIMPLI-FLYD tool has a set of specifications intended as a first attempt at a "generic" set requirements. Of course, a framework exists for the definition of more tailored sets of HQ requirements in that the criteria used by SIMPLI-FLYD are mainly drawn from ADS-33E and MIL-STD-1797B both of which already feature categorization of requirements and multiple boundaries for different aircraft types and mission roles. However, it is not yet clear what is most appropriate at conceptual design: is it a more generic set that can be applied for a variety of designs and roles to drive an initial "conceptual design level" of handling qualities requirements; or perhaps the ability to set optional specification sets for differing design requirements is a more valid approach?

Another key aspect relates to the setting of the HQ requirements boundaries themselves. A great deal of research underpins the metrics and the boundaries between Level 1, 2 and 3 boundaries, however the models themselves are simplified and are based on a relatively low level of data and design “clarity”. This all introduces uncertainty, via the accuracy of the models and of the data they are based on, an issue that only becomes greater when trying to predict the characteristics of unfamiliar new vehicle configurations. Many of the emerging designs are featuring multiple rotors, wings, control surfaces and other auxiliary propulsion devices which are likely to exhibit a degree of aerodynamic interactions between them, something that is notoriously difficult to predict even with high fidelity simulation codes. Getting a better answer through the use of such modeling is also still not a practicable approach for conceptual design. Although the verification results in this paper have shown that the modeling used in this toolset is able to reasonably predict the flight dynamics characteristics of a variety (albeit well-known) of rotorcraft configurations, it seems that building in a certain amount conservativeness into the requirements will be necessary.

The application of the CONDUIT concept of design margin (DM) may well be an important factor in addressing this. Indeed, the original concept for the design margin in CONDUIT is to compensate for uncertainty in the vehicle dynamics and account for off-nominal conditions when designing control laws (Ref. 16) – this is conceptually akin to the uncertainty in the predicted dynamics in the simplified modeling and data of SIMPLI-FLYD. Establishing those margins will likely require design test cases that are carried forward to higher fidelity detailed analyses.

As was concluded in the study preceding this work in Ref. 1, incorporating a control system produces overall flight dynamic and control models that are more realistic, and make analysis of the often unstable designs more tractable. However, the incorporation of CONDUIT is a significantly more sophisticated approach over the aforementioned work and this comes at the cost that direct correlations between the HQ outcomes and design changes are increasingly obfuscated by the optimized control system compensation. As was highlighted in the results section, the influence of the actuator characteristics is a critical factor. Their specification not only limit the overall maximum control response but their application in conjunction with a model-following control law architecture mean that the ability to meet many of the response requirements end up being a function of the vehicle’s control authority/bandwidth required to track the desired response specified by the command model.

Of course, the underlying bare-airframe characteristics are still playing an important part in the HQ outcomes but the actuator characteristics play almost an equally prominent role in the overall outcome. As such, care should be applied in defining their characteristics. Furthermore, an important factor for conceptual design will be the correlation of the assigned actuator performance with a weight/cost/tech factor in the overall conceptual design so that the “cost” of actuators are properly accounted for.

CONCLUDING REMARKS

This paper has demonstrated the development and capability of the SIMPLI-FLYD toolset for performing flight dynamics and control and handling qualities analysis of rotorcraft conceptual designs. The toolset possesses the following main features:

- Ability to automatically model the flight dynamics and control characteristics of multiple rotorcraft configurations and flight conditions.
- Automatically integrates the flight dynamics models into a model following control system architecture for analysis in CONDUIT.
- Output of handling qualities and stability and control parameters, charts, and control system design margins for multiple axes and flight conditions/configurations.
- Ability to automatically generate a model that can be operated in pilot-in-the-loop real time simulation in X-Plane.

The test cases using the UH-60A and tiltrotor demonstrated sensitivity of the handling qualities parameter output to simple design parameter variations. The establishment of the SIMPLI-FLYD toolset now permits exploration of the broader research questions pertaining to the incorporation of HQ analysis such as type of criteria to be applied, their HQ “Level” boundaries, and how the outcomes are used in the vehicle conceptual design process.

Appendix

Table 7 Rotor-borne Hover Feedback Specifications

Spec Name	Description (Motivation)	Source	Axis	Design Margin
	Hard Constraints			
EigLcG1	Eignevalues in L.H.P. (Stability)	Generic	All	
StbMgG1	Gain Phase Margin broken at actuator (Stability)	MIL-DLT-9490E	All	
NicMgG1	Nichols Margins broken at actuator (Stability)	GARTEUR	All	
	Soft Constraints			
ModFoG2	Command model following cost (HQ)	Generic	All	
DrbRoH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Roll	✓
DrbPiH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Pitch	✓
DrbYaH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Yaw	✓
DstBwG1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Heave	✓
DrpAvH1	Disturbance Rejection Peak (HQ, Ride Quality)	ADS-33E	All	
OlpOpG1	Open Loop Onset Point (PIO)	DLR	All	
EigDpG1	Eigenvalue Damping, 0.5-4 rad/sec (HQ, Loads)	ADS-33E	All	
EigDpG1	Eigenvalue Damping, 4-20 rad/sec (HQ, Loads)	ADS-33E	All	
CrsMnG1	Minimum crossover frequency (Robustness)	Generic	All	✓
	Summed Objectives			
CrsLnG1	Crossover Frequency (Actuator Activity)	Generic	All	
RmsAcG1	Actuator RMS (Actuator Activity)	Generic	All	

Table 8 Rotor-borne Hover Feed-Forward Specifications

Spec Name	Description (Motivation)	Source	Axis	Design Margin
	Soft Constraints			
BnwAtH1	Attitude bandwidth, phase delay (HQ)	ADS-33E	Roll, Pitch	✓
BnwYaH2	Heading bandwidth, phase delay (HQ)	ADS-33E	Yaw	✓
FrqHeH2	Heave mode time constant (HQ)	ADS-33E	Heave	✓
MaxRoH2	Minimum achievable roll rate (HQ)	ADS-33E	Roll	✓
MaxPiH2	Minimum achievable pitch rate (HQ)	ADS-33E	Pitch	✓
MaxYaH2	Minimum achievable yaw rate (HQ)	ADS-33E	Yaw	✓
MaxHeH1	Minimum achievable vertical rate (HQ)	ADS-33E	Heave	✓
QikRoH2	Roll attitude quickness (HQ)	ADS-33E	Roll	✓
QikPiH2	Pitch attitude quickness (HQ)	ADS-33E	Pitch	✓
QikYaH2	Heading quickness (HQ)	ADS-33E	Yaw	✓
OlpOpG1	Open Loop Onset Point (PIO)	DLR	All	
	Summed Objectives			
RmsAcG1	Actuator RMS (Actuator Activity)	Generic	All	

Table 9 Rotor-borne Forward-Flight Feedback Specifications

Spec Name	Description (Motivation)	Source	Axis	Design Margin
	Hard Constraints			
EigLcG1	Eignevalues in L.H.P. (Stability)	Generic	All	
StbMgG1	Gain Phase Margin broken at actuator (Stability)	MIL-DLT-9490E	All	
NicMgG1	Nichols Margins broken at actuator (Stability)	GARTEUR	All	
	Soft Constraints			
ModFoG2	Command model following cost (HQ)	Generic	All	
DrbRoH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Roll	✓
DrbPiH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Pitch	✓
DrbYaH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Yaw	✓
DstBwG1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Heave	✓
DrpAvH1	Disturbance Rejection Peak (HQ, Ride Quality)	ADS-33E	All	
OlpOpG1	Open Loop Onset Point (PIO)	DLR	All	
EigDpG1	Eigenvalue Damping, 0.5-4 rad/sec (HQ, Loads)	ADS-33E	All	
EigDpG1	Eigenvalue Damping, 4-20 rad/sec (HQ, Loads)	ADS-33E	All	
CrsMnG1	Minimum crossover frequency (Robustness)	Generic	All	✓
	Summed Objectives			
CrsLnG1	Crossover Frequency (Actuator Activity)	Generic	All	
RmsAcG1	Actuator RMS (Actuator Activity)	Generic	All	

Table 10 Rotor-borne Hover Feed-Forward Specifications

Spec Name	Description (Motivation)	Source	Axis	Design Margin
	Soft Constraints			
BnwRoF3	Roll attitude bandwidth, phase delay (HQ)	ADS-33E	Roll	✓
BnwPiF3	Pitch attitude bandwidth, phase delay (HQ)	ADS-33E	Pitch	✓
BnwYaH2	Heading bandwidth, phase delay (HQ)	ADS-33E	Yaw	✓
FrqHeF1	Heave mode time constant (HQ)	ADS-33E	Heave	✓
MaxRoF1	Minimum achievable roll rate (HQ)	ADS-33E	Roll	✓
MaxPiF1	Minimum achievable pitch rate (HQ)	ADS-33E	Pitch	✓
MaxYaF1	Minimum achievable yaw rate (HQ)	ADS-33E	Yaw	✓
MaxHeH1	Minimum achievable vertical rate (HQ)	ADS-33E	Heave	✓
QikRoF2	Roll attitude quickness (HQ)	ADS-33E	Roll	✓
OlpOpG1	Open Loop Onset Point (PIO)	DLR	All	
	Summed Objectives			
RmsAcG1	Actuator RMS (Actuator Activity)	Generic	All	

Table 11 Wing-borne Forward-Flight Feedback Specifications

Spec Name	Description (Motivation)	Source	Axis	Design Margin
	Hard Constraints			
EigLcG1	Eignevalues in L.H.P. (Stability)	Generic	All	
StbMgG1	Gain Phase Margin broken at actuator (Stability)	MIL-DLT-9490E	All	
NicMgG1	Nichols Margins broken at actuator (Stability)	GARTEUR	All	
	Soft Constraints			
ModFoG2	Command model following cost (HQ)	Generic	All	
DrbRoH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Roll	✓
DrbPiH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Pitch	✓
DrbYaH1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Yaw	✓
DstBwG1	Disturbance Rejection Bandwidth (HQ, Ride Quality)	ADS-33E	Heave	✓
DrpAvH1	Disturbance Rejection Peak (HQ, Ride Quality)	ADS-33E	All	
OlpOpG1	Open Loop Onset Point (PIO)	DLR	All	
EigDpG1	Eigenvalue Damping, 0.5-4 rad/sec (HQ, Loads)	ADS-33E	All	
EigDpG1	Eigenvalue Damping, 4-20 rad/sec (HQ, Loads)	ADS-33E	All	
CrsMnG1	Minimum crossover frequency (Robustness)	Generic	All	✓
	Summed Objectives			
CrsLnG1	Crossover Frequency (Actuator Activity)	Generic	All	
RmsAcG1	Actuator RMS (Actuator Activity)	Generic	All	

Table 12 Wing-borne Hover Feed-Forward Specifications

Spec Name	Description (Motivation)	Source	Axis	Design Margin
	Soft Constraints			
BnwRoD1	Roll attitude bandwidth, phase delay (HQ)	MIL-STD-1797B	Roll	✓
RolPfD1	Time to bank (HQ)	MIL-STD-1797B	Roll	✓
MaxYaD1	Minimum achievable yaw rate (HQ)	MIL-STD-1797B	Yaw	✓
DmpDrD2	Dutch roll damping ratio (HQ)	MIL-STD-1797B	Yaw	
FrqDrD3	Dutch roll frequency (HQ)	MIL-STD-1797B	Yaw	
FrqRoD4	Roll mode time constant (HQ)	MIL-STD-1797B	Roll	
TdlRoD1	Equivalent roll axis time delay (HQ, PIO)	MIL-STD-1797B	Roll	
TdlYaD1	Equivalent yaw axis time delay (HQ, PIO)	MIL-STD-1797B	Yaw	
BnwFpL2	Flight path bandwidth, phase delay (HQ)	MIL-STD-1797B	Pitch	✓
BnwPiL4	Pitch attitude bandwidth, phase delay (HQ)	MIL-STD-1797B	Pitch	✓
MaxPiF1	Minimum achievable pitch rate (HQ)	ADS-33E	Pitch	✓
DrpPiL1	Pitch attitude dropback	MIL-STD-1797B	Pitch	
TdlPiL1	Equivalent pitch axis time delay (HQ, PIO)	MIL-STD-1797B	Pitch	
CapPiL2	Control anticipation parameter (HQ)	MIL-STD-1797B	Pitch	
OlpOpG1	Open Loop Onset Point (PIO)	DLR	All	
	Summed Objectives			
RmsAcG1	Actuator RMS (Actuator Activity)	Generic	All	

ACKNOWLEDGMENTS

A number of individuals are acknowledged for their input and advice in this work. At NASA Ames Research Center, Dr. Wayne Johnson is thanked for his NDARC expertise and technical consultation on conceptual design. Also at NASA Ames, Dr. Carlos Malpica is thanked for many technical discussions and for his consultation on rotor modeling. Jeff Keller of Continuum Dynamics Inc. is thanked for his support with the X-Plane shared memory interface development. A former NASA Ames Research Center Aeromechanics office intern, Nando Van Arnhem, is also acknowledged for laying the foundations of the SIMPLI-FLYD/X-Plane interface code. John Davis, of Daviation Technologies is acknowledged for technical consultation and for documentation. Finally, Bruce Tenney, US Army retired, is acknowledged for his leadership in initiating the project that encompassed this work.

REFERENCES

[1]Morris, C. C., Sultan, C., Allison, D. L., Schetz, J. A., & Kapania, R. K., "Towards Flying Qualities Constraints in the Multidisciplinary Design Optimization of a Supersonic Tailless Aircraft.", 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM, 17-19 Sep 2012, Indianapolis, IN, USA.

[2]Padfield, G. D. "Rotorcraft Handling Qualities Engineering; managing the tension between safety and performance". *Journal of the American Helicopter Society*, 58 (1). 1 – 28, 2013.

[3]Lawrence B., "Incorporating Handling Qualities Analysis into Rotorcraft Conceptual Design", American Helicopter Society Rotorcraft Handling Qualities Specialists' Meeting Proceedings, Huntsville, AL, February 19-20, 2014.

[4]Johnson, W., "NDARC — NASA Design and Analysis of Rotorcraft, Theoretical Basis and Architecture", American Helicopter Society Aeromechanics Specialists' Conference Proceedings, San Francisco, CA, January 20-22, 2010.

[5]Tischler, M. B., Colbourne, J., Morel, M., Biezad, D., Cheung, K., Levine, W., and Moldoveanu, V., "A Multidisciplinary Flight Control Development Environment and Its Application to a Helicopter," IEEE Control Systems Magazine, Vol. 19, No. 4, pg. 22-33, August, 1999.

[6]Tischler, M. B., Remple, R. K., *Aircraft and Rotorcraft System Identification: Engineering Methods and Flight Test Examples*, 2nd Edition, AIAA, 2012, pp 332-333.

[7]Schulein, G. J., Tischler, M. B., Mansur, M. H., & Rosen, A. (2002). Technical Note: "Validation of Cross-Coupling Modeling Improvements for UH-60 Flight Mechanics Simulations." *Journal of the American Helicopter Society*, Vol. 47(3), pp. 209-213.

[8]Mitchell, David G., Roger H. Hoh, Chengjian He, and Kristopher Strope. "Determination of maximum unnoticeable added dynamics." AIAA Atmospheric Flight Mechanics Conf. and Exhibit Proceedings, Keystone, CO, pp. 21-24. 2006.

[9]Juhasz, Ondrej, Roberto Celi, Christina M. Ivler, Mark B. Tischler, and Tom Berger. "Flight dynamic simulation modeling of large flexible tiltrotor aircraft." Proc. American Helicopter Society 68th Annual Forum, Fort Worth, TX, 2012.

[10]Anon., "Handling Qualities Requirements for Military Rotorcraft", Aeronautical Design Standard-33 (ADS-33E-PRF), US Army Aviation and Missile Command, March 21, 2000.

[11]Anon., "Flying Qualities of Piloted Aircraft," MIL-STD-1797B, Department of Defense Interface Standard, February, 2006.

[12]Lehmann, R., Tischler, M. B., Blanken, C.L., "Evaluation of ADS-33E Yaw Bandwidth and Attitude Quickness Boundaries", Proc. American Helicopter Society 72nd Annual Forum, West Palm Beach, FL, 2016.

[13]Zivan, L., Tischler, M.B., "Development of a Full Flight Envelope Helicopter Simulation Using System Identification", *Journal of the American Helicopter Society*, Vol 55, No. 2, April 2010.

[14]Lawrence, B., Malpica, C. A., Theodore, C. R., "The Development of A Large Civil Tiltrotor Simulation for Hover and Low-Speed Handling Qualities Investigations", 36th European Rotorcraft Forum Proceedings, Paris, France, Sep 7-9th, 2010.

[15]Marcos, A., Balas, G.J., "Development of Linear-Parameter-Varying Models for Aircraft", *AIAA Journal of Guidance, Control, and Dynamics*, Mar-Apr 2004, 0731-5090 vol.27 no.2 (218-228).

[16]Tischler, M. B., Ivler, C. M., Mansur, M. H., Cheung, K. K., Berger, T., Berrios, M. G., "Handling-Qualities Optimization and Trade-offs in Rotorcraft Flight Control Design," RAeS Rotorcraft Handling-Qualities Conference, November 4-6, 2008, University of Liverpool, United Kingdom.